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TITLE OF THE INVENTION

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Topographic Measurement Using Stereoscopic Picture Frames

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BACKGROUND OF THE INVENTION

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Field of the Invention

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The present invention relates generally to topographic measurement of a target area using image sensors mounted on flying vehicles such as earth observation satellites.

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Description of the Related Art

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Topographic measurement using stereoscopic pictures is known as remote sensing technology. In one topographic measurement system known as a cross-track stereoscopic imaging system, a single image sensor (HRV and AVNIR sensors) mounted on a satellite (SPOT and ADEOS satellites) is used to capture a number of pictures of a target area at different times when the satellite is encircling on separate orbits. In other system known as an along-track imaging system, use is made of two image sensors (OPS and PRISM sensors) on board a single satellite (JERS-1 and ALOS satellites) to capture multiple pictures of a target area at different angles when the satellite is encircling on the same orbit over the target area. While the latter is able to send pictures at frequent intervals, hence available stereoscopic pictures can be easily obtained, a high-capacity memory is required on board the ship to store pictures before transmission to the earth. However, in applications where a high resolution of one meter is desired, the cross-track stereoscopic imaging has been preferred to the along-track stereoscopic imaging.

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A recent advance in the remote sensing technology is the development of an earth observation satellite such as IKONOS and Quick Bird satellites in which a single sensor performs the functions of both cross-track imaging and along-track imaging systems.

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When a pair of stereoscopic pictures is sensed, the pictures are scanned line by line and transmitted from the satellite in the form of frames to the earth station. The transmitted frames are analyzed in terms of point-to-point

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1 correlations between the frames to determine how much they differ from one
2 another. This correlation information is known as parallax. Using a model of
3 the image sensor, a position is determined in a three-dimensional coordinate
4 system for each point-to-point correlation. A set of such 3-D position data
5 obtained from a target area constitutes topographic data of the target area.

6 However, in order to sense a target area from an earth observation
7 satellite, it is necessary to ensure that, when the satellite is approaching the
8 target area, it is bright under sun light and not shadowed by any cloud.
9 Chances for taking appropriate pictures are therefore limited. In particular,
10 in applications where high resolution is desired, a single-sensor, cross-track
11 earth observation satellite will be used. When the satellite is approaching a
12 target area, the sensor must be pointed toward the target area from different
13 angles at different times to obtain a pair of stereoscopic frames. Therefore,
14 the target area must be clear and bright for both chances of image sensing.
15 Additionally, the target area must be pointed from relatively large angles.
16 This requires that the satellite orbits be distanced sufficiently from each other.
17 During the time the satellite is encircling on intermediate orbits, no
18 appropriate pictures cannot be taken, which leads to a low efficiency of
19 satellite utilization. Therefore, target areas suitable for acquiring stereoscopic
20 pictures are significantly limited.

SUMMARY OF THE INVENTION

22 It is therefore an object of the present invention to provide a
23 topographic data processor and a topographic measurement system which
24 can acquire stereoscopic picture frames with high efficiency of satellite
25 utilization.

26 The stated object is obtained by the provision of a frame pair selector
27 for selecting a pair of picture frames that constitute a stereoscopic image from
28 multiple frames which may be stored in a storage medium or received from
29 one or more satellites.

30 According to a first aspect of the present invention, there is provided a

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1 topographic data processor comprising means for selecting a pair of frames
2 from a plurality of candidate frames of a target area captured from different
3 high-altitude positions, the pair of frames constituting a stereoscopic image of
4 the target area, means for determining a parallax between the selected frames
5 and producing therefrom a first plurality of line-of-sight vectors and a second
6 plurality of line-of-sight vectors, and means for converting the first and
7 second pluralities of line-of-sight vectors to topographic data.

8 A best frame pair is selected by first forming candidate picture frames
9 into a plurality of pairs of stereoscopic frames and then evaluating the frame
10 pairs with fitness values representative of their fitness to topographic
11 measurement and selecting a best frame pair having the highest fitness value.

12 According to a second aspect, the present invention provides a
13 topographic data processor comprising frame selecting means for selecting a
14 pair of frames from a plurality of candidate frames of a target area captured
15 from high-altitude positions, the selected pair of frames constituting a
16 stereoscopic image of the target area. Scheduling means is provided for
17 selecting at least one airborne image sensor if an appropriate frame is not
18 available in the plurality of candidate frames and sensing picture frames from
19 the selected image sensor, whereby the frame selecting means uses the sensed
20 frames to select a pair of frames. A parallax calculation means is provided for
21 determining a parallax between the frames selected by the frame selecting
22 means and producing therefrom a first plurality of line-of-sight vectors and a
23 second plurality of line-of-sight vectors. The first and second pluralities of
24 line-of-sight vectors are converted to topographic data.

25 According to a third aspect of the present invention, there is provided
26 a topographic measurement system comprising at least one image sensor
27 mounted on a vehicle flying over a target area, a receiver for receiving a
28 plurality of picture frames captured by the image sensor at different
29 positions, means for selecting a pair of frames from the plurality of frames,
30 the pair of frames constituting a stereoscopic image of the target area, means

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1 for determining a parallax between the selected frames and producing
2 therefrom a first plurality of line-of-sight vectors and a second plurality of
3 line-of-sight vectors, and means for converting the first and second pluralities
4 of line-of-sight vectors to topographic data.

5 According to a fourth aspect of the present invention, there is
6 provided a topographic measurement system comprising at least one image
7 sensor mounted on a vehicle flying over a target area, a receiver for receiving
8 a plurality of picture frames captured by the image sensor at different
9 positions, frame selecting means for selecting a pair of frames from the
10 plurality of frames of the target area, the selected pair of frames constituting a
11 stereoscopic image of the target area, scheduling means for selecting at least
12 one image sensor if an appropriate frame is not available in the plurality of
13 frames, sensing picture frames from the selected image sensor, whereby the
14 frame selecting means uses the sensed frames to select a pair of frames,
15 means for determining a parallax between the frames selected by the frame
16 selecting means and producing therefrom a first plurality of line-of-sight
17 vectors and a second plurality of line-of-sight vectors, and means for
18 converting the first and second pluralities of line-of-sight vectors to
19 topographic data.

20 BRIEF DESCRIPTION OF THE DRAWINGS

21 The present invention will be described in detail further with reference
22 to the following drawings, in which:

23 Fig. 1 is a schematic diagram of a land observation system according to
24 a first embodiment of the present invention;

25 Fig. 2 is a block diagram of a topographic data processor of the first
26 embodiment of the present invention;

27 Fig. 3 is a block diagram of the frame pair selector of the topographic
28 data processor;

29 Figs. 4 and 5 are schematic diagrams useful for describing the
30 operation of the geometric condition analyzer of the topographic data

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1 processor;

2 Fig. 6 is a block diagram of the parallax calculator of the topographic
3 data processor;

4 Fig. 7 is a schematic diagram useful for describing the operation of the
5 parallax calculator;

6 Fig. 8 is a flowchart useful for describing the operation of the first
7 embodiment of the present invention;

8 Fig. 9 is a block diagram of a topographic data processor of a second
9 embodiment of the present invention;

10 Fig. 10 is a block diagram of an image sensing scheduler of Fig. 9;

11 Fig. 11 is a schematic diagram useful for describing the operation of a
12 geometric condition analyzer of Fig. 10; and

13 Fig. 12 is a flowchart useful for describing the operation of the second
14 embodiment of the present invention.

DETAILED DESCRIPTION

16 Referring now to Figs. 1 and 2, there is shown a land observation
17 system according to a first embodiment of the present invention. The system
18 includes a first land observation satellite 11 encircling the earth on an orbit 16
19 and a second land observation satellite 12 encircling the earth on an orbit 17
20 spaced from the orbit 16. Each satellite is constantly capturing images of the
21 land surface including a target area 13. Specifically, the satellite 11 includes a
22 two-dimensional CCD sensor 21 and a high-precision telescope, not shown,
23 for focusing the image of a land surface onto the CCD sensor 21 and an RF
24 transmitter 23. Likewise, the satellite 12 includes a two-dimensional CCD
25 sensor 22 and a high-precision telescope, not shown, for focusing the image
26 of a land surface onto the CCD sensor 22 and an RF transmitter 24.

27 The images (picture frames) captured by both satellites are transmitted
28 on a downlink frequency from the transmitters 23 and 24 to an earth station
29 14 where the RF signals are amplified and down-converted to baseband
30 signals by an RF transceiver 25. The signals received from both satellites are

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1 stored in a storage medium 27 which may be provided in a topographic data
2 processor 15. In this way, the storage medium 27 stores a series of picture
3 frames of land surfaces captured by satellites 11 and 12.

4 As will be described in detail later, a pair of picture frames which form
5 a stereoscopic image adequate for the determination of the altitude of a
6 surface feature of a target area is selected by a frame pair selector 28 from the
7 storage medium 27. The selected pair of picture frames are supplied to a
8 parallax calculator 29 to detect a parallax between the selected frames. Based
9 on the calculated parallax, the parallax calculator 29 produces a first plurality
10 of line-of-sight vectors from one of the selected frames and a second plurality
11 of line-of-sight vectors from the other frame. A parallax-terrain converter 30
12 is connected to the output of the parallax calculator 29 to produce
13 topographic data based on the first plurality of line-of-sight vectors and the
14 second plurality of line-of-sight vectors. The topographic data is supplied to
15 output means 31.

16 As illustrated in detail in Fig. 3, the frame pair selector 28 comprises a
17 decision module 40, a frame combiner 41 and a plurality of analyzers 42 to 46.

18 Since the picture frames captured by the satellites may contain images
19 which cover outside of the target area 13, the frame combiner 41 first selects
20 only those picture frames covering the target area and proceeds to combine
21 picture frames selected from those captured by satellite 11 with frames
22 selected from those captured by satellite 12 to form a plurality of frame pairs
23 each composing a stereoscopic image of the target area. If a frame consists of
24 red, green, blue and near-infrared light components, these components are
25 not treated individually in so far as their resolutions are equal to each other.
26 Since panchromatic images have in most cases twice as high resolution as
27 red, green and blue components, they are treated separately from the color
28 components. All pairs of frames combined by the frame combiner 41 are
29 supplied to all analyzers 42 to 46 as candidate frame pairs.

30 Analyzers 42 to 46 perform individual analysis on the candidate frame

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1 pairs according to different visual characteristics and evaluate each pair of
2 frames with a set of fitness values Q₁ through Q₆ each being representative
3 of the fitness of the frame pair to topographic measurement of the target area.

4 For each frame pair, the decision module 40 scales the fitness values
5 with respective weight values w_i and totals the weighted fitness values w_iQ_i
6 to produce a quality value Q of the frame pair. The process is repeated on all
7 frame pairs and finally the decision module 40 selects one of the frame pairs
8 having the highest quality value as a best frame pair.

9 Analyzer 42 is a geometric condition analyzer which evaluates the
10 candidate frame pairs and determines a weight value Q₁ according to
11 geometric conditions of the frame of each pair, such as the resolution (i.e., an
12 area covered by a single pixel and measured in terms of meters) or the angles
13 of orientation of the satellites to the land surface. In a simple yet effective
14 method, a pair of high-resolution frames is evaluated with a high weight
15 value.

16 If the frames of a pair are of different resolution, the frame of lower
17 resolution is chosen to evaluate the pair. The evaluation of a pair with lower
18 resolution is preferred to evaluating the pair with an average value of the
19 resolutions of its frames. In this case, the fitness value Q₁ is given as:

20
$$Q_1 = 1 / \text{Resolution} \quad (1)$$

21 If high precision is important for the frame pair evaluation, quantum
22 errors of the frames of each pair are used to evaluate the pair. In principle,
23 this method involves determining a displacement in a three-dimensional
24 space between the frames of a stereoscopic pair on a pixel-by-pixel basis and
25 representing it a quantum error in a system of three-dimensional axes.

26 Assume that the image sensors of satellites 11 and 12 are pointing
27 toward a target point "o" in a three-dimensional coordinate system (x, y, z)
28 with its x and y axes pointing North and East, respectively, on the earth
29 surface 18 (which is approximated as a flat plane), and its z axis pointing
30 skyward, as shown in Fig. 4. The image sensor of satellite 11 is located in a

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1 position s_1 of altitude h_1 from the ground point g_1 , azimuth angle a_1 and
 2 angle of elevation e_1 , while the image sensor of satellite 12 is located in a
 3 position s_2 of altitude h_2 from the ground point g_2 , azimuth angle a_2 and
 4 angle of elevation e_2 . Ground points g_1 and g_2 are at distances b_1 and b_2
 5 from the point of origin o , respectively, and mutually spaced at distance b_3 .
 6 Points o , g_1 and g_2 form a triangle with inner angles a_3 , a_4 and a_5 , and points
 7 o , s_1 and s_2 form a triangle, called epipolar plane 50. A portion of the
 8 epipolar plane 50 in the neighborhood of the point of origin "o" can be
 9 enlarged as shown in Fig. 5 to illustrate its details to the size of pixels.

10 In Fig. 5, adjacent pixels on the image sensor of satellite 11 are
 11 indicated as p_{11} and p_{12} from which line-of-sight vectors v_{11} and v_{12} extend
 12 toward the point of origin. Likewise, adjacent pixels on the image sensor of
 13 satellite 12 are indicated as p_{21} and p_{22} from which line-of-sight vectors v_{21}
 14 and v_{22} extend toward the point of origin. Horizontal distance r_1 between
 15 line-of-sight vectors v_{11} and v_{12} represents the resolution of the image sensor
 16 of satellite 11 and horizontal distance r_2 between line-of-sight vectors v_{21} and
 17 v_{22} represents the resolution of the image sensor of satellite 12.

18 On the epipolar plane 50, the line-of-sight vector v_{12} forms an angle e_1'
 19 to the earth surface 18 and the line-of-sight vector v_{22} forms an angle e_2' to
 20 the earth surface 18. The angles e_1' , e_2' and the resolutions r_1 , r_2 are given as
 21 follows:

$$22 \quad e_1' = \arctan \{ h_1 / b_1 \cos a_3 \} \quad (2a)$$

$$23 \quad e_2' = \arctan \{ h_2 / b_2 \cos a_4 \} \quad (2b)$$

$$24 \quad r_1 = r_1' \sin e_1' \quad (3a)$$

$$25 \quad r_2 = r_2' \sin e_2' \quad (3b)$$

26 where r_1' and r_2' are the resolutions of the sensors of satellites 11 and 12
 27 when they directly point to ground points g_1 and g_2 , respectively.

28 The quantum error at the point of origin "o" is represented by an area
 29 50A defined by line segments c_1-c_2 , c_2-c_3 , c_3-c_4 and c_4-c_1 . Therefore, a
 30 stereoscopic image whose area 50A is small is evaluated with a high fitness

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1 value since the size of the area 50A determines the resolution of the image.
 2 The quantum error is decomposed into a horizontal component E_h and a
 3 vertical component E_v which are given as follows:

$$4 E_h = (r_1' \tan e_1' + r_2' \tan e_2') / (\tan e_1' + \tan e_2') \quad (4a)$$

$$5 E_v = (r_1' + r_2') (\tan e_1') (\tan e_2') / (\tan e_1' + \tan e_2') \quad (4b)$$

6 It is seen that the fitness value $Q1$ of a frame pair is inversely
 7 proportional to its quantum error as given by the following relations:

$$8 Q1 = 1 \text{ (if } E_h < E_{h_req} \text{ and } E_v < E_{v_req}) \\ 9 = 0 \text{ (otherwise)} \quad (5)$$

10 where E_{h_req} and E_{v_req} are threshold values of E_h and E_v .

11 Alternatively, the fitness value $Q1$ can be determined as:

$$12 Q1 = q_1/E_h + 1/E_v \quad (6)$$

13 where q_1 represents a parameter of positive value for giving different
 14 weights to the error components E_h and E_v . In most cases, the parameter
 15 q_1 is equal to unity. In comparison with other analyzers, the geometric
 16 condition analyzer 42 plays a significant role for selecting a best frame pair
 17 from the candidate frame pairs.

18 Analyzer 43 is a filtering condition analyzer which evaluates the frame
 19 pairs from the frame combiner 41 in terms of their weight to topographic
 20 measurement which varies depending on the filtering characteristics of the
 21 satellite image sensors. Picture frames obtained by a satellite image sensor
 22 with the full spectrum of visible light, i.e., panchromatic images, are usually
 23 of high S/N quality and fitting to topographic measurement. If two frames
 24 are obtained by image sensors of like filtering characteristics, they are also
 25 suitable to form a pair for topographic measurement since they are less
 26 affected by differences in filtering characteristics when a parallax is calculated
 27 between them. Therefore, the filtering condition analyzer 43 evaluates the
 28 frames of each candidate pair with a fitness value $Q2$ which is proportional to
 29 the amount of visible spectral components they have obtained as a result of
 30 the filtering characteristics of the satellite sensors as well as to the likeness of

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1 their wavelength characteristics to each other. The fitness value Q2 is
 2 expressed by the following formula:

$$3 \quad Q2 = \frac{\int_S f(w)g(w)dw}{S} \quad (7)$$

4 where, S indicates the spectrum of visible light, w is the wavelength, and f(w)
 5 and g(w) represent the filtering characteristics of the image sensors of
 6 satellites 11 and 12, respectively (i.e., the transmissibility of filtered visible
 7 wavelengths incident on the image sensors). The functions f(w) and g(w) are
 8 of high value if the transmissibility of wavelengths is high. Equation (7) thus
 9 indicates that greater the filtering functions overlap each other the fitness
 10 value Q2 becomes higher. The panchromatic image is given the highest Q2
 11 value.

12 Analyzer 44 is a sunlight condition analyzer which evaluates the
 13 frames of each candidate pair with a fitness value Q3 in terms of their weight
 14 to the calculation of parallax which varies depending on the sunlight
 15 condition under which the frames are captured. If sunlight conditions under
 16 which frames of a pair are captured are substantially equal to each other,
 17 their images will show similar shadow and shading effects to each other.
 18 Since the frames of like sunlight conditions result in an accurate parallax,
 19 they are evaluated with high fitness value Q3.

20 The following is an evaluation formula for the fitness value Q3:

$$21 \quad Q3 = 1 \text{ (if } |a_1 - a_2| < d \text{ and } |e_1 - e_2| < d\text{)} \\ 22 \quad = 0 \text{ (otherwise)} \quad (8)$$

23 where, d is a threshold angle of several degrees. Equation (8) indicates that
 24 Q3 is high if azimuth angles a_1 and a_2 and angles of elevation e_1 and e_2 are
 25 almost equal to each other. If their differences exceed the threshold angle, the
 26 influence of sunlight conditions on frames remains constant.

27 Analyzer 44 is a time-difference analyzer which evaluates the frame
 28 pairs from the frame combiner 41 in terms of their weight to topographic
 29 measurement which varies depending on the time difference between the

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1 frames of each pair. Since the time difference between frames (two or three
2 seconds, for example) may result in objects pictured in one frame taking
3 different shapes and positions from those of the other, a high fitness value Q4
4 is given to a pair of frames whose time difference is small. However, the time
5 difference may vary significantly depending on the orbits of satellites and
6 other factors.

7 Q4 is given as follows:

8
$$Q4 = \exp(-T_d)$$
 (9)

9 where T_d is the absolute value of difference between the pictured timings of
10 the frames and represented by the number of days. The fitness value Q4 may
11 also be given by observing frame pictures by human eyes. If the pictures of
12 any two frames differ substantially, a low value of Q4 is manually given to
13 these frames.

14 Analyzer 46 is a frame matching analyzer that evaluates each pair of
15 combined frames with a fitness value Q5 in terms of their degree of match
16 between the combined frames. The degree of match between frames of each
17 pair is determined by an average value of correlation values obtained by the
18 parallax calculator 29 for each frame pair as follows:

19
$$Q5 = AVs$$
 (10)

20 As will be described later, the parallax calculator 29 defines windows
21 (the size of a few pixels) in corresponding positions of the frames of a pair
22 and obtains correlation values between the windows. Frame matching
23 analyzer 46 averages the correlation values (between -1 and 1) obtained by
24 the parallax calculator 29. If the average value of correlations between frames
25 of a pair is high, it is considered that there is a high degree of match between
26 the frames and the frame pair is evaluated with a high fitness value Q5.

27 It is seen from the foregoing that, for each frame pair, a set of fitness
28 values Q1 ~ Q5 is obtained. The same process is repeated until a plurality of
29 sets of fitness values Q1 ~ Q5 are obtained from all frame pairs formed by the
30 frame combiner 41.

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1 Specifically, the decision module 40 calculates the following Equation
 2 by respectively weighting the fitness values of a frame pair to obtain a total
 3 value of weighted fitness value as a quality value Q of the frame pair:

4
$$Q = w_1 Q_1 + w_2 Q_2 + w_3 Q_3 + w_4 Q_4 + w_5 Q_5 \quad (11)$$

5 where, w_1 through w_5 are weight values for the analyzers 42 through 46.

6 One example of the weight values is:

7
$$w_1 = 10 \text{ and } w_2 = w_3 = w_4 = w_5 = 1$$

8 If the frame pair selector 28 is provided with only one analyzer, i.e.,
 9 the geometric condition analyzer 42, the weight value w_1 is set equal to unity
 10 and all other weight values are set equal to zero.

11 Decision module 40 repeats the same process on all frame pairs
 12 supplied from all analyzers to produce their quality values Q and selects one
 13 of the frame pair having the highest quality value.

14 As shown in Fig. 6, the parallax calculator 29, connected to the output
 15 of the frame pair selector 28, includes an interpolator 61, a frame aligner 62
 16 and a correlation calculator 63. If frames of different resolutions are selected
 17 as a best pair by the frame pair selector 28, the frame of lower resolution is
 18 supplied to the interpolator 61 to improve its resolution so that it is equal to
 19 the resolution of the other frame. The frames are then supplied to the frame
 20 aligner 62, where the frames are aligned so that they are parallel with an
 21 epipolar line of a stereoscopic image. The aligned frames are fed into the
 22 correlation calculator 63.

23 As shown in Fig. 7, the correlation calculator 63 segments each of the
 24 aligned frames into rectangular windows of several pixels on each side and
 25 takes correlation between windows A and B of corresponding positions to
 26 determine a correlation value $r_{j,k}$ as follows:

$$r_{j,k} = \frac{\sum_{j} \sum_{k} \{(I(A, j, k) - M(A))(I(B, j, k) - M(B))\}}{\sqrt{\sum_{j} \sum_{k} \{I(A, j, k) - M(A)^2\}} \sqrt{\sum_{j} \sum_{k} \{I(B, j, k) - M(B)^2\}}} \quad (12)$$

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1 where, $I(A, j, k)$ is the pixel value of point (j, k) of the window A, $I(B, j, k)$ is
2 the pixel value of point (j, k) of the window B, and $M(A)$ is the average of
3 pixel values of window A, and $M(B)$ is the average of pixel values of window
4 B.

5 By successively shifting the positions of the windows A and B pixel by
6 pixel and calculating correlation values, the analyzer 46 seeks relative
7 positions of windows A and B where there is a peak or maximum correlation
8 value. When such positions are detected, the analyzer 46 produces output
9 data indicating the corresponding relationship between the center pixel of
10 window A and the center pixel of window B. The above process is repeated
11 for all windows of the frames to obtain a plurality of frame-to-frame
12 corresponding relationships (i.e., line-of-sight vectors) as parallax data.

13 On the other hand, the parallax data are obtained from all frame pairs
14 supplied from the frame pair selector 28 are fed back to the frame matching
15 analyzer 46. When this occurs, the decision module of the frame pair selector
16 28 receives all sets of weight data Q_1 to Q_5 from the analyzers 42 to 46 and
17 selects a best frame pair and commands the correlation calculator 63 to
18 supply the parallax data of the best frame pair to the parallax-terrain
19 converter 30.

20 In more detail, as previously described with reference to Fig. 5, if
21 pixels p_{11} and p_{22} correspond to each other, the intersection point c_1 of line-
22 of-sight vectors v_{11} and v_{22} lies on a surface feature of the target area. In
23 order to obtain a plurality of such intersection points in a three-dimensional
24 coordinate system to produce topographic data, this conversion process is
25 repeated for all line-of-sight vectors represented by the parallax data to
26 describe all surface features of the target area.

27 Parallax-terrain converter 30 performs a parallax-terrain conversion
28 process by using the line-of-sight vectors indicated by the parallax data of the
29 selected frame pair to produce terrain data which represents surface features
30 of the target area.

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1 Topographic data is supplied from the parallax-terrain converter 30 to
2 output means 31 such as display or memory.

3 Due to the provision of the frame pair selector 28, picture frames taken
4 by any pair of multiple image sensors can be selected for producing
5 topographic data, eliminating the inability to produce topographic data due
6 to the absence of stereoscopic images and enabling the selection of best
7 stereoscopic images for particular purposes.

8 Fig. 8 is a flowchart which summarizes the operation of the first
9 embodiment of the present invention. At step 81, the satellites 11 and 12 are
10 encircling the earth to capture photographic images of various regions of the
11 earth on predetermined schedule. The captured images are scanned and
12 transmitted to the earth station 14 and stored in storage medium 27 (step 82).
13 In response to demand for creating topographic data, a plurality of frame
14 pairs containing a target area are selected from the storage medium (step 83).
15 Parallax is calculated between the frames of each selected pair (step 84).
16 When parallax is calculated for all frame pairs, a best frame pair is selected
17 (step 85). Line-of-sight vectors indicated by the parallax data of the best
18 frame pair are used to produce topographic data (step 86) and utilized for
19 display, storage or transmission (step 87).

20 In the first embodiment of this invention, topographic data is
21 produced exclusively from the stored data in the storage medium 27. If
22 appropriate frames are not available in the storage medium, no topographic
23 data is obtained.

24 A second embodiment of the present invention, shown in Fig. 9, is
25 intended to solve this problem. In Fig. 9, parts corresponding to those in Fig.
26 2 are marked with the same numerals and the description thereof is omitted.
27 In this embodiment, the system additionally includes an image sensing
28 scheduler 90 which is connected to the frame pair selector 28 and to the RF
29 transceiver 25. The decision module of frame pair selector 28 checks to see if
30 there is no usable frame or if the parallax data of the best frame pair is not

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1 usable. In either case, the frame pair selector 28 instructs the image sensing
2 scheduler 91 to proceed with the formulation of an image sensing schedule.
3 According to the formulated schedule, the scheduler 90 sends a sensing
4 command signal to one or more earth observation satellites 91 via the RF
5 transceiver 25.

6 As shown in Fig. 10, the scheduler 90 includes a decision module 100, a
7 satellite selector 101, a geometric condition analyzer 102, a filtering condition
8 analyzer 103, a sunlight condition analyzer 104, a time-difference analyzer
9 105 and a frame matching analyzer 106.

10 Satellite selector 101 is responsive to the instruction from the frame
11 pair selector 28 to select one or more earth observation satellites which cover
12 the target area and send picture frames within a scheduled interval of time,
13 which may be ten minutes or as long as several months. If a satellite is flying
14 over the same area several times during a known time interval, the image
15 sensor of the same satellite is treated as a separate sensor as long as the
16 pictures are captured at different angles to the target area. According to the
17 instruction from the frame pair selector 28, the satellite selector 101 receives
18 picture frames of the selected satellites from the RF transceiver 25 and
19 supplies the received frames to the modules 102, 103, 104 and analyzers 105,
20 106.

21 Geometric condition analyzer 102 combines the picture frames
22 supplied from the satellite selector 101 into a plurality of pairs of frames that
23 compose stereoscopic images and supplies the pairs of combined frames to
24 the other analyzers 103 to 106. Analyzer 102 further informs the decision
25 module 100 of the identifiers of the satellites from which the paired picture
26 frames are obtained. As described previously with respect to the geometric
27 condition analyzer 42, the geometric condition analyzer 102 calculates the
28 quantum errors of the combined frames of each stereoscopic pair and assigns
29 a fitness value Q6 to each frame pair so that a highest value Q6 is given to a
30 frame pair of smallest quantum error.

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1 The operation of the geometric condition analyzer 101 for detecting
2 quantum errors between two picture frames will be described with reference
3 to Fig. 11.

4 Assume that satellites 11 and 12 are selected by the satellite selector
5 101, respectively encircling the earth on orbits 16 and 17 that cover the target
6 area 13. A first set of sensing points $p_{1-1} \sim p_{1-5}$ are established at intervals
7 along the orbit 16, and a second set of sensing points $p_{2-1} \sim p_{2-6}$ are
8 established at intervals along the orbit 17. Picture frames at the sensing
9 points are then paired between the first and second sets, such as between
10 point p_{1-3} and point p_{2-1} , for example. For each pair of sensing points, a
11 quantum error is then calculated between the frames at the sensing points
12 and the pair of sensing points is evaluated with a fitness value Q6 as follows:

$$13 \quad Q_6 = q_6/E_h + 1/E_v \quad . \quad (13)$$

14 where q_6 is a positive weight value which is usually equal to unity. High
15 Q_6 value is assigned to a frame pair if the horizontal and vertical components
16 of the quantum error are small.

17 If more than two satellites are selected, sensing points are established
18 in the same manner as discussed above. If only one new picture frame is
19 desired, using a stored frame as its companion, Equation (13) is calculated by
20 assuming that there is only one fixed sensing point for one of the satellites.

21 Filtering condition analyzer 103, the sunlight condition analyzer 104,
22 the time difference analyzer 105 and the frame matching analyzer 106
23 correspond respectively to the filtering condition analyzer 43, sunlight
24 condition analyzer 44, time difference analyzer 45 and frame matching
25 analyzer 45, and operate in like manner to that described previously to
26 produce fitness values Q7, Q8, Q9 and Q10.

27 Decision module 100 makes a decision on the fitness values Q6 ~ Q10
28 of each frame pair and produces a total of weighted fitness values (quality
29 value) Q of the frame pair as follows:

$$Q = w_6 Q6 + w_7 Q7 + w_8 Q8 + w_9 Q9 + w_{10} Q10 \quad (14)$$

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1 where, $w_6 \sim w_{10}$ are weight values of the corresponding fitness values Q_6 to
2 Q_{10} . If use is made of only the geometric condition analyzer 102, the weight
3 value w_6 is set equal to 1 and all the other weight values are set to zero.

4 Based on the total fitness value Q , the decision module 100 formulates
5 an image sensing schedule. The schedule includes data identifying satellites
6 to be used, sensing positions, sensing times and filtering conditions.

7 According to the schedule, the decision module 100 sends a command signal
8 to one or more satellites through the transmitter 92.

9 Fig. 12 is a flowchart which summarizes the operation of the second
10 embodiment of the present invention. At step 121, frame pair selection is
11 performed to select a plurality of pairs of frames from the storage medium 27.
12 At decision step 122, decision is made as to whether or not usable frames are
13 available. If the selected frames are usable for producing topographic data,
14 flow proceeds to step 123 to perform parallax calculation and select a best
15 frame pair. At step 124, decision is made as to whether or not parallax data of
16 the best frame pair is usable. If the decision is affirmative, flow proceeds to
17 step 125 to perform parallax-terrain conversion to produce topographic data
18 which is output to a display or the like (step 126).

19 If the decision at step 122 or 124 is negative, flow proceeds to step 127
20 to formulate an image sensing schedule and transmit a command signal to
21 one or more satellites (step 128) and returns to step 121.